ON THE UTILISATION OF

HEAT AND OTHER NATURAL FORCES:

A LECTURE

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The supremacy which man enjoys over the animate and inanimate creation, and for which Divine Authority may be quoted, cannot be said to be the result of his superior muscular development, for amongst the members of the animal kingdom there are many which are his superiors in strength, agility, swiftness, and in natural aptitude to provide themselves against the vicissitudes of cold and hunger. Who has not looked with a feeling akin to envy upon the deer in watching its swift progress to the mountain top, or on the eagle soaring majestically aloft, while feeling his own insufficiency of power to play lightly with the force of gravity!

The compensating advantage in our favour is the intelligence with which we are enabled to call forces of nature not our own into requisition to do our behests. Man in his most primitive condition already commences to exercise his mastery over nature, by having recourse to the sling and the arrow for reaching his prey, by taking advantage of animal power to draw the plough, and when in exchanging his commodities for those of neighbouring people, both his merchandise and himself are carried by beasts of burthen, who tamely submit their superior muscular energy to his will.

At another stage we find man utilising the inanimate forces of nature by causing the falling stream to give motion to the millstone, or by calling into requisition the force of the wind for propelling him along the surface of

the waters; and following his progress step by step, we finally arrive at our own condition of social existence, in which we are dependent upon the power of steam for propelling us both by land and sea at a speed rivalling that of our friends the deer and the eagle, and for accomplishing for us the innumerable purposes of grinding, spinning, pumping, and lifting, upon which our material well-being now depends. It would not be too much to say that the power of man consists really in his ability to direct the forces of nature, and that the degree of civilisation to which he has attained is commensurate with his command of those forces. It is therefore no idle question on which I intend to address you this evening, and I feel much oppressed with the weight of matter which I have to bring before you, although I shall not attempt to deal with more than a few points, to which I hope to be able to attract your interest.

In order to understand the forces of nature, and to direct their application, it is necessary that we should at least have a general conception of their origin. The time was not long ago when the forces in nature appeared to us as spasmodic and unconnected, when the energy of the wind and of the falling stream, the energy displayed in vegetation and in muscular action, the force of heat and the almost unknown force of electricity appeared to have no connection with one another, and seemed to be beyond the reach of human calculation.

The probability of connecting-links between the different forces of nature has, however, presented itself to some of the greatest minds of different ages; thus, Aristotle "considered the first principle in nature to be a unity of all its manifestations, and the manifestations themselves he reduced always to motion as their foundation." Again, in Lord Bacon's *Aphorisms*, the chapter on "The First Vintages of the Force of Heat" contains the following remarkable passage:—"From the instances taken collectively, as well as singly, the nature whose limit is heat appears to be motion." And further on, "But that the very essence of heat, or the substantial self of heat, is motion, and nothing else limited," &c. Bacon fails, however, in his attempts to

prove his philosophy, by confounding the visible motion of heating water, or of fire, with the intrinsic motion of the particles that manifests itself as heat.

Count Rumford, in 1798, made the first important advance to connect heat with mechanical force, supporting his theory by means of experiments which were intended to determine the actual numerical relation between them, and we observe with surprise how near his experimental results approached to the now-accepted determination of the mechanical equivalent of heat.

Sir Humphrey Davy caused the fusion of two pieces of ice by friction, and thus virtually proved the identity of heat and motion, though he failed to give expression to that view.

Carnot, in 1824, sought to determine how heat produced mechanical work; and although, in one respect, he appears to have receded from the views already advanced by others before him, in speaking of heat as a subtle fluid, he makes the remarkable statement that the greatest possible work an engine can perform is a function of the temperatures between which it works, and not of the nature of the substance employed. He also was the first to draw attention to the important fact that in working a caloric engine some heat must necessarily descend from a higher to a lower point of temperature, whereas another portion disappears in the operation.

The next and most important step in the advancement of this branch of science we owe to the independent investigations of three discoverers—viz., Grove of London, Mayer of Heilbronn, and Joule of Manchester—three men whose modes of thought differed very widely from each other, but who each of them pronounced distinctly the complete identity of all physical forces, proving their mutual convertibility coupled with complete indestructibility. To Dr. Joule we owe, moreover, the determination of the numerical equivalent in units of heat by which mechanical effect is measured.

But although the mechanical equivalents of heat, as well as those of electricity and chemical affinity, were thus absolutely established, much remained to be ac-

complished to assign to the new theory its actual signification. This was done independently and by different methods by Professor Clausius in Germany, and by your own illustrious townsmen, Rankine and Sir William Thomson, in this country. The two former, starting from different hypotheses, determined the general equation of thermodynamics which expresses the relation between heat and mechanical energy under all circumstances: while the latter, in building upon the basis of Carnot and Joule, solved some important new problems in thermodynamics, and extended analogous principles to electricity and magnetism, thereby creating what may justly be termed a new science. Other names, including those of Seguin, Helmholz, and Tait should not be passed over without mention.

The popular volume entitled *Heat a Mode of Motion*, which was produced in 1863 by Professor Tyndall, also did valuable service by introducing to the larger scientific public a knowledge of this most important new branch of science, and by terminating for ever the view which had generally prevailed up to that time, according to which heat and electricity were regarded as subtle fluids or imponderable substances. According to present views, all the agencies in nature may be defined as energy, varying only in their outward manifestations, as heat or as electricity, as chemical affinity or as mechanical effect, and presenting themselves as sensible or kinetic energy, or as dormant or potential energy.

Thus, when I lift a pound weight one foot high, muscular kinetic energy is exercised, causing a certain consumption of the potential energy resident in the muscle of the arm; in suspending it, the force thus exerted becomes so much stored up, or potential energy, which may at any time be called into requisition for the accomplishment of various purposes. Thus, if attached to a string passing over a pulley, it may be made to impart motion to a train of wheels for driving a clock, or to accomplish any other kind of mechanical work. Again, if allowed to drop from its elevated position upon a plate of glass, it may produce the mechanical effect of breaking the sheet of glass into fragments, causing at the same time considerable sound,

whilst, if allowed to fall upon a sheet of lead, it will cause an indentation without producing appreciable sound ; but if in this instance we could have measured the temperature of the lead before it was struck, and again immediately after, we should be able to detect a certain increase of heat, the amount of which is absolutely determined by Joule's equivalent ; thus, if the piece of lead were one pound in weight and were equally heated throughout, by the shock of the falling weight of 1 lb. through 1 foot, 772 repetitions of the same would produce heat sufficient to raise its temperature 34°·13 Fahrenheit, which would again be equivalent to the heating of one pound of water 1° Fahrenheit, or to the unit of heat. Or our potential force of one foot-pound could be utilised to produce magnetism and an electric current by means of a machine (the dynamo-electric machine) which I shall have occasion to describe to you presently, which electric current may in its turn be utilised to produce light such as at present illuminates this hall. By means of the same dynamo-electric apparatus our unit of force could be utilised to cause the separation of chemical compounds, accomplishing, for instance, the deposit of copper of definite amount from its solution.

It may be said generally that without energy both in its kinetic and potential forms it would be impossible to imagine the very existence of life, of vegetation, and indeed of material creation. It is by molecular or potential energy that the particles of all matter, whether solid, liquid, or gaseous, are maintained in their relative position ; it is by an augmentation of this form of energy that ice is changed into water, and by a further augmentation that water is changed into steam or vapour, giving rise through its withdrawal to rainfall, with all its attendant benefits, to vegetation ; whilst it is by the potential energy residing in coal that we derive warmth, cook our food, and work our factories.

Whence, it may be asked, is all this energy derived? Is it that our earth constitutes herself a mine of potential energy, which we have only to tap and utilise for our purposes? A little examination into this question will convince us that we have no such store to fall back upon, and

that, excepting the coal, there is nothing within our earth to yield us a supply of energy. The water of the ocean is the result of the combustion of hydrogen which may have taken place at some early period of the earth's history, when it must have given rise to an enormous generation of heat; enough, perhaps, to constitute our planet a luminary body; but this combustion having been once accomplished, this energy is irrecoverably lost to us, excepting the small remnant which prevents the water from assuming the solid form, and which is unavailable for our purposes.

If we examine the solid constituents of the earth, such as the siliceous or calcareous rocks, we shall find that they also are the result of former combustion; in the case of the mountain limestone we find that, on heating it, it separates into two substances, calcic oxide, a solid, and carbonic acid, a gaseous body. In examining each of these constituents we find that they also are the results of combustion, the one of the metal calcium, and the other of the metalloid carbon; a combustion which must also have been accomplished at an early period of the earth's history. Other rocks we find to be the product of combustion of aluminium, magnesium, silicon, and other chemical elements; and only comparatively rare substances, such as gold, platinum, and copper, besides native sulphur and pyrites, may still be looked upon as stores of potential energy. Excepting these, and the important deposits of coal, the earth may indeed be likened to a ball of cinder, whose energy has long been spent and dissipated into space, and which is dependent for its supply of energy upon external sources. Without such external supply, the water upon its surface would be turned into solid ice, its animal and vegetable kingdom must soon come to an end, rain must cease to fall, and the very winds must cease to blow. It is not now difficult to conceive whence the all-vivifying energy to which we owe our existence is derived; it is from our great luminary—the Sun.

It has been justly remarked that poetic vision sometimes goes beyond the conception of the sober mind, and there never, perhaps, lived a poet who was more remarkable for such distant vision than Goethe, who, in his famous tragedy of *Faust* has accumulated an almost inexhaustible store

for thoughtful meditation. Faust, in his eagerness for knowledge, conjures up into his presence a spirit, which reveals itself to him as the Spirit of the Earth in the following remarkable words, according to the translation of Mr. Theodore Martin:—

> " In the currents of life, in action's storm,
> I wander and I wave;
> Everywhere I be!
> Birth and the grave,
> An infinite sea;
> A web ever growing,
> A life ever glowing.
> Thus at Time's whizzing loom I spin,
> And weave the living vesture that God is mantled in."

Surely Goethe was free from vulgar superstition, and must have conceived that his Spirit of the Earth represented an entity capable of precise definition, whenever science had sufficiently advanced to render such a definition possible. Such an advance has since been made, and Goethe's Spirit of the Earth presents itself to us as the all-animating, all-vivifying solar ray, by which our earth is clad, and to which we owe our material existence.

The coal itself, which yields us so important a supply of energy, is no exception to this rule, being only the result of vegetation in former ages, when the ray of the sun separated carbon from carbonic acid of the atmosphere in the leaves of plants in the same manner in which it does to-day, and thus made for us a store of accumulated carbon, or, metaphorically speaking, of accumulated sunbeams which may be called large, but which, in view of our ever increasing requirements, must become exhausted, not indeed in our lifetime, but in the lifetime of those who follow us in comparatively few generations to come.

According to the Report of the Coal Commissioners, published in 1871, there were then nearly 150,000,000,000 of tons of coal available in Great Britain. The present rate of consumption is about 132,000,000 of tons annually, and statistics show that there is a mean annual increase in the output of 3⅓ millions of tons, and a calculation at this rate of increase would give 250 years as the life of

our coal-fields. It must be borne in mind, however, that long before the last ton of coal is brought to the surface, the effect of its gradual failure will have made itself painfully manifest. Districts whose industry is most active and populations largest, will first experience the change, and it behoves us to consider in good time what resources, if any, we shall have to fall back upon.

I have shown that the universal source of energy is the sun, but there is one important exception, namely, the force of the tidal wave. This is of cosmical origin, depending upon the acquired rotation of the earth, as influenced by the local attraction exercised upon it by the moon and the sun, and, if utilised, would tend to a gradual reduction in the course of ages of the earth's rotative velocity. The amount of available energy represented by this source is vast indeed, but cannot be utilised to a large extent, except in comparatively few localities and at great inconvenience and expense.

For all practical purposes we depend upon the solar ray past and present for our supply of useful energy, and when we shall have consumed the stores produced in former ages, we must be content to live with it from hand to mouth. This condition of things may satisfy the negro in Central Africa or the agriculturist of Southern Europe, who lives on the fruit of the land, but cannot but appear highly unsatisfactory to an audience such as I have the honour of addressing.

The sun makes his appearance to the inhabitants of Glasgow at somewhat rare intervals, I am told, and it might be supposed from this fact that his action is correspondingly unimportant to their well-being. Such is not, however, the case, as it can easily be proved that the action of the solar ray is as potential in its results at Glasgow as in Central Africa. The very clouds that so frequently obstruct the direct rays of the sun are the result of his evaporative effect exercised upon the Atlantic Ocean. The steam raised there by the sun's heat condenses when driven by the prevailing south-west wind against your elevated shores, and, in condensing, produces a temperature which makes your northern climate as temperate almost as that

of Southern Europe. You are furnished at the same time with an abundance of rain water, which, as I shall presently show, could be made serviceable for a supply of mechanical power, and even of heat and light, to an amount vastly superior to the total energy you now derive from coal.

These observations may suffice to define generally our present standpoint of scientific knowledge regarding energy in its different forms. It is not my purpose to penetrate deeper into this new branch of science, which we owe to the illustrious persons whose names I have mentioned, but my task is the more humble, though, perhaps, not less useful one of considering some of the applications of this science for our material wants. It is in this direction that my individual efforts have been exerted ever since the year 1846, when, fired up by the first announcement of the labours of Carnot, Grove, Joule, and Mayer, I conceived the possibility of realising at least a portion of the economical results revealed to us by scientific research.

An inquiry into the economical results of the caloric motors of the day, by the light of the Dynamical Theory of Heat, revealed to me the fact that the best steam engine of that day yielded only about $\frac{1}{10}$ part of the mechanical effect of the heat consumed, the remaining $\frac{9}{10}$ being lost in the form of heated products of combustion passing away up the chimney, and in heating the water inside the condenser. It appeared as though the great inheritance bequeathed to us by Watt, had nearly accomplished its mission, and that we had reached another starting-point in applied science commensurate to the one then just accomplished in pure science.

It was evident, that in order to produce greater results, higher temperatures had to be resorted to, and it was equally evident, that inasmuch as the range of the elastic fluid giving motion to a working piston was necessarily limited, it would not be possible to convert the whole of the heat that had been employed in producing the highly heated elastic medium into onward motion of the piston, and that, therefore, a method had to be devised for storing

the residue of the heat contained in the elastic medium after the accomplishment of each stroke of the engine. Such an appliance presented itself ready-made in the regenerator, or heat recuperator, as it might be more appropriately called, a contrivance which had been suggested as far back as 1817 by the Rev. Robert Stirling, of Dundee, and which was afterwards applied to a heated air engine by his brother, Mr. James Stirling.

I will not inflict upon you a detailed description of the engine resulting from these reflections, nor an account of the innumerable difficulties and disappointments to which they led. Suffice it to say that I obtained economical results sufficient to prove the correctness of the principles upon which I had gone to work, but the complete practical realisation of those principles (involving, as it does, the use of steam or air very highly heated under pressure) is a matter which has yet to be achieved, as the endeavours of James Stirling, Ericsson, and other pioneers in the same field, have not led to any more satisfactory results than my own.

On the other hand, the steam-engine constructed upon the general principles laid down by James Watt has undergone some important changes; these consist of improved modes of firing, improved construction of boilers, the introduction of surface condensation, and such modifications in the construction of the engine itself as enable us to carry into effect the expansive action of steam to a much greater extent than formerly. These improvements have been introduced more particularly into the marine-engine, a class of engines which fifteen years ago compared unfavourably as regards economical results with land-engines, particularly with such as were used for pumping water, known as the Cornish engine, and for giving motion to large factories, for which the double cylinder, or Woolff engine, had come largely into use. It is due in great measure to the energies of one of your naval constructors, the late Mr. John Elder, that a more economical marine-engine has been brought into use in the shape of a modification of Woolff's engine, in which the crank of the high-pressure cylinder is placed at right angles to that of the low-pressure or expansive cylinder, whereby the important advantage is realised that a single

pair of cylinders produces a continuity of driving power throughout the revolution of the engine-shaft.

The economical results obtained through the introduction of these improvements are strikingly illustrated by the fact that one-horse power is now produced with an expenditure of 2 lbs. of coal per hour, whereas in the most economical marine-engines fifteen years ago double the amount was employed.

The calorific effect residing in one pound of pure carbon, if burnt under the most favourable circumstances (producing carbonic acid as the result of combustion), is 14,000 heat units; but common coal, containing an average amount of ash, moisture, and absorbed carbonic acid may be taken at 12,000 units with perfect combustion. These represent $12,000 \times 772 = 9,264,000$ ft. lbs. of force; and the two pounds of coal consumed per horse-power represent twice that amount, or 18,528,000 ft. lbs., whereas one-horse power is represented by $33,000 \times 60 = 1,980,000$ ft. lbs. per hour. This comparison brings us to the conclusion that the best steam-engine of the day utilises only about *one-ninth part* of the heat producible by the combustion of the fuel employed.

But it must be remembered that although force may be converted entirely into its equivalent of heat, heat cannot be converted into force without loss, through heat descending from a point of higher energy or temperature to a lower point, the amount of force realisable being dependent upon the range between the maximum and minimum temperatures, or, in the case of an elastic fluid engine, the temperature before and after expansion.

An engine capable of developing one-horse power with two pounds of coal per hour, is worked with a pressure of 60 pounds above the atmosphere, or 74·7 pounds on the square inch, with a corresponding initial temperature of 307° Fahr., and a pressure in the condenser of 1 pound on the square inch, corresponding to 105° Fahr.; we find, by taking the ratio of the difference of these numbers to that of the greater given in absolute degrees of temperature, that the efficiency of the steam is

$$\frac{307 - 105}{307 + 461} = \frac{202}{768}$$

But we must also consider the loss of effect carried away by the heated products of combustion. The temperature of the fire may be taken at 2500°, and that of the chimney at 500° Fahr., above the atmospheric temperature, and the ratio of the difference of these numbers to the greater gives

$$\frac{2500-500}{2500}=\frac{4}{5}$$

as the efficiency of the furnace, which agrees with that of the best regulated furnaces worked with chimney draught.

By the multiplication together of these ratios we obtain the combined theoretical efficiency of

$$\frac{202}{768}\times\frac{4}{5}=\frac{808}{3840}=\frac{2}{9}\text{ (approximately)}$$

of the steam and furnace worked upon the best known and approved principles.

Thus it is shown that the best steam-engines now constructed are capable of realising $\frac{2}{9}$ of the heat generated in the combustion of the fuel under the boiler, whilst the remaining $\frac{7}{9}$ form the margin for future improvement. A large margin, it must be owned, and one that can be dealt with only by increasing the range of temperatures, the most perfect engine being one in which the temperature ranges from that produced in combustion, say, 3000° Fahr., to the minimum temperature producible in a condenser.

The production of mechanical work is, however, not the only, nor indeed the most important employment of fuel; its largest consumption takes place in the smelting and re-heating of metals and other substances. Here, again, the actual results obtained are very much below those indicated by scientific inquiry.

Great improvements have, indeed, been effected in blast furnace economy by the introduction of the hot blast by Nielson. Yet, if we consider the conversion of iron ore into finished products, such as wrought iron or steel, as a connected process, we find that there remains a very large

margin for improvement; and ultimate economical results can only be looked for, I venture to think, when the several operations now employed are replaced by a direct or single process of conversion.

In order to heat a pound of iron to the welding point (say, 2700° Fahr.), the number of heat units absorbed by the iron does not exceed, according to the best authorities, about 900, which would be producible with about

$$\frac{900}{12000} = 0\cdot075 \text{ lb. of coal.}$$

In an ordinary furnace, the coal burned to heat a ton of iron to the welding point amounts to about 12 cwts., or ·6 lb. of coal per pound of iron, making the actual consumption eight times that indicated by theory.

Again, in melting a ton of steel in pots the number of heat units actually absorbed by the metal may be roughly estimated at about 1800 units per pound weight, whereas the fuel actually consumed to melt a ton of mild steel in pots amounts to 3 tons in the dense form of coke, or $3 \times 12{,}000 = 36{,}000$ units per pound of steel melted.

Here we find that the actual consumption exceeds the theoretical in the ratio of 20 : 1,—without taking into consideration the loss of effect which had already taken place in converting the coal into coke.

Here is a field for effecting a saving in fuel which has particularly occupied my attention for a number of years, and, with your permission, I will give you a description of the means resorted to by myself and my brother, Frederick Siemens, who is associated with me in these improvements, to accomplish more economical results.

These consist in the combination of an apparatus for the entire conversion of fuel into unrefined gas, with a furnace constructed upon the regenerative principle, suitable for the combustion of such gaseous fuel.

The gas-producer, Fig. 1, is a rectangular fire-brick chamber, one side, B, inclined at an angle of from 45° to 60°, and provided with a grate, C, at the foot, through which passes a regulated quantity of air. Fuel is filled in through a hopper, A, at the top of the incline, and carbonic acid gas is

the first result of combustion taking place at the foot of the producers. The carbonic acid gas thus produced, in passing through the thick stratum of incandescent fuel above, is converted into carbonic oxide, while some of the surplus heat distils the hydrocarbons in the fuel on the incline. Below

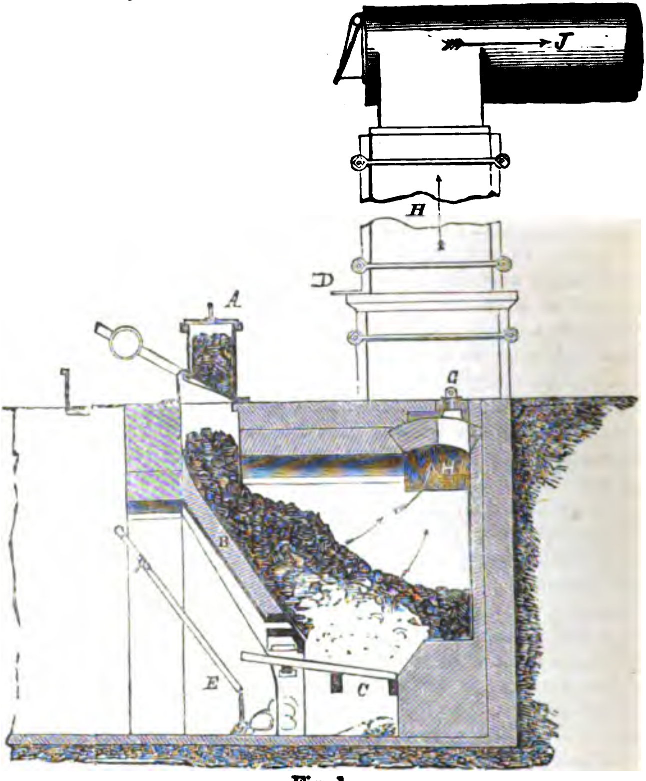

Fig. 1.

the grate water is supplied in limited quantity, E, which is decomposed into its elements, by heat which would otherwise be lost by radiation into the atmosphere, and thus enriches

the gas by the addition of hydrogen and the formation of carbonic oxide free from nitrogen. This mixture of gases passes up a brick stack, H, and is then carried through a horizontal "elevated cooling tube," J, wherein a certain amount of the energy of sensible heat is transformed into that of pressure, in which form it is required for two reasons; firstly, that there may be no leakage of air into the gas flue, and, secondly, that the gas may be delivered with a slight outward pressure at the furnace.

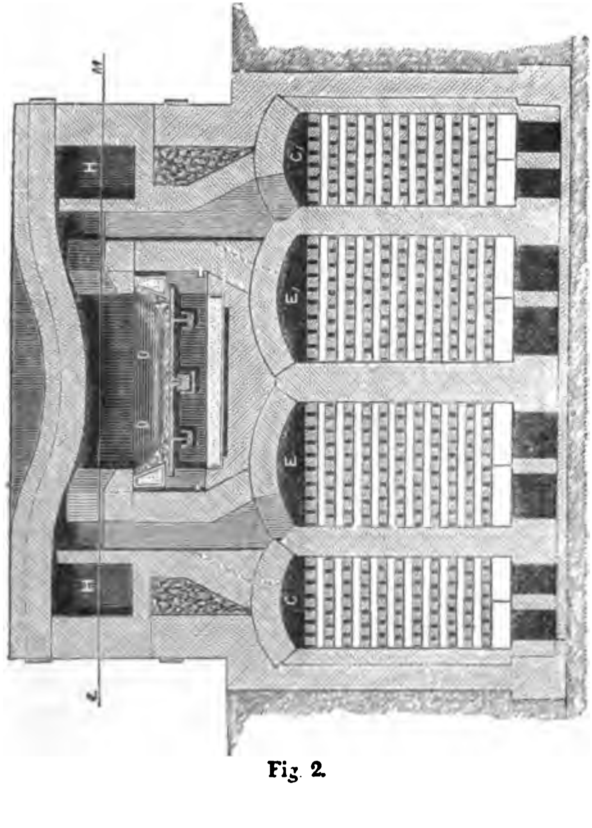

Fig. 2.

The furnace consists of the regenerators, valves, and heating chamber. The regenerators are four chambers, C, E, Fig. 2, containing fire-bricks so arranged as to allow air or gas to pass through them : these fire-bricks will be heated by hot gas, and will heat cool air or gas passing through the chambers. The regenerators are divided into pairs of two, which are connected with special reversing

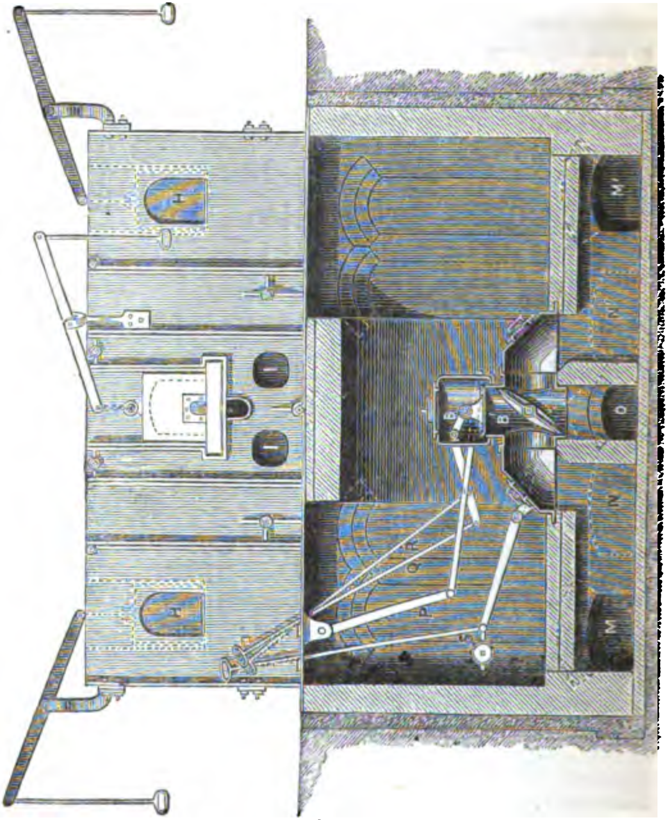

Fig. 3.

valves, B, B, Fig. 3, so arranged that the gas-regenerator of the admission pair is connected with the gas-producer, and the air-regenerator with the atmosphere, while the products of combustion pass through the exit regenerators to the chimney. The reversing valves are arranged like four-way cocks, so that by throwing over the flaps the admission regenerators may become exit regenerators, and *vice versâ*. The heating chamber, D, is placed above the regenerators, and there are two sets of ports leading from it to the two pairs of regenerators.

When the furnace is in action, and at a certain high temperature, air enters the air-regenerator from the atmosphere, and gas the gas-regenerator from the producer; these currents are heated as they traverse the brickwork of their respective regenerators, and finally combine in the furnace, adding the heat of the brickwork through which they have passed to that of chemical combination or combustion. The flame produced having done its work in the heating chamber, the products of combustion pass down the exit regenerators, which they heat to a high temperature.

After a certain time, generally half an hour, the direction of the currents is reversed by means of the reversing valves, the exit regenerators becoming those of admission; and thus each pair of regenerators is alternately employed to heat the entering air and gas, and to cool the products of combustion, which finally leave the chimney at a comparatively low temperature.

By this arrangement of furnace great economy is attained, great cleanliness of working and purity of flame; but it has been principally valuable, as owing to the great heat obtainable, it has enabled metallurgical processes to be effected, which cannot be attempted in ordinary furnaces. The temperature is limited theoretically by the point of dissociation (or the point at which the energy of chemical affinity is overcome by that of sensible heat), and practically by the resistance to fusion offered by the refractory materials employed in the construction of the furnace. The economy is proved by the fact that a ton of iron can be heated to the welding point with 7 cwts. of coal; and a ton of steel melted

with 12 cwts., whilst from 2 to 3 tons of coke were formerly employed to produce the same effect.

Having thus dealt with the two principal applications of coal to useful purposes, I pass over its manifold other applications for domestic and general uses, and ask you to accompany me to the consideration of that other great store of energy, the tidal wave. In order to utilise this, large basins or reservoirs would have to be provided along the shore of the tidal sea or estuary, to be filled with tidal water during the flood, and to be discharged during the ebb of the tide. The energy of the inflowing and outflowing stream of water can best be utilised by means of such turbine or vortex-wheel as we owe to Professor James Thomson, and is a matter with which I need not detain you at present. What I wish to show is, what is the amount of power recoverable with a given area of tidal basin, and a given rise or fall of tide.

Suppose the actual rise of tide to be 12 feet, 8 feet would be available during half the time of the rise or fall, which would be equivalent to an effective head of 4 feet during the twenty-hours, what is the power that can be utilised per acre of surface? An acre of ground contains 43,560 square feet, and the weight of sea water is 64 lbs. per cubic foot; multiplying these numbers into the height of fall, and dividing by the equivalent of 1 horse-power, we obtain 5·6 horse-power as the effective energy of an acre of impounded sea water. Considering the great cost of constructing sea walls to form these tidal basins, and considering also the value of the foreshores in estuaries, or protected portions of the seashore, where alone such constructions would be practicable, it will be at once apparent that the utilisation of the tidal wave is both costly and restricted in its application. Although the force is apparently obtained without expenditure, the intermittance of the supply, the interest upon the outlay, the cost of maintenance, and the tendency for such basins to silt up are drawbacks of such serious nature that we may dismiss the question of the utilisation of this source of natural energy from serious consideration.

But what about the utilisation of the sources of energy

depending upon the solar ray from day to day. It has been calculated that the total calorific effect produced by solar rays upon the surface of this globe would be sufficient in amount to evaporate annually an ocean of boiling water covering the whole surface to the depth of 14 feet, or to melt a stratum of ice of upwards of 100 feet in thickness.

In order to produce the same calorific effect by means of a theoretically perfect furnace, we must consider what quantity of water is represented by a depth of 14 feet over the surface of the earth. The earth's mean diameter is about 42,000,000 feet in round numbers, and its mean circumference is 132,000,000 feet, and the multiplication of these numbers gives its surface as 5,500,000,000,000,000 of square feet. If we multiply this by the depth of 14 ft., and by the density of water, 62·4, we obtain 77,000,000,000,000,000 of cubic feet, equal to nearly 5,000,000,000,000,000,000 of pounds of water.

The heat which evaporates a pound of water, in a perfect boiler, is about 1000 heat units, so that a pound of coal will evaporate 12 lbs. of water, and a ton of coal about 27,000 lbs. We shall therefore require, taking only round numbers, about 180,000,000,000,000 of tons of coal per annum to perform the effect of the sun's rays upon the earth's surface. This quantity is about 660,000 times as great as the total quantity of coal raised annually throughout the world.

These figures prove that after all we are not so entirely dependent upon the solar energy of former days, represented by coal, as we have been apt to suppose; but that, on the contrary, a vastly superior supply of solar energy comes to us, year by year, by direct radiation, which at the present time is actively employed in producing summer and winter, the fertilising rain, the gentle winds, the raging storm, and all those other natural effects which we behold, but which we have not yet had occasion to utilise for our specific purposes, except to a very small extent. The application of natural forces has, indeed, yielded in recent times to what may be called the artificial employment of coal; the ancient water-wheel has in many cases gone to ruin, windmills no longer crowd the elevated ground near our towns

and villages, and the steam funnel, with its flag of suffocating smoke, has superseded, to a great extent, the more graceful but less certain sail for the propulsion of our vessels. This change has been the natural consequence of the abundant supply of coal which we now enjoy; but this supply, as I have endeavoured to show, is not without limit, and the time will come when man will have to revert to those natural forces upon which he has for the present turned his back.

It would, however, be wrong to suppose that a resumption of the use of natural forces would throw us back to the time of the windmill and the primitive water-wheel which used to give motion to isolated establishments. We shall have learned to store, to transport, and to utilise these forces in a manner adapted to our superior requirements; and who knows whether the time may not come when our descendants in the third or fourth generation will look back upon the indiscriminate users of coal with something like the same feeling that we look upon the users of flint and bronze implements. Indeed, without waiting for the extinction of our coal-fields, it appears to me not improbable that natural forces will be resorted to simply on account of their comparative cheapness and convenience of application.

When little more than a twelvemonth ago I visited the great falls of Niagara, I was particularly struck with the extraordinary amount of force which is lost, as far as the useful purposes of man are concerned. 100,000,000 of tons of water fall there every hour from a vertical height of 150 feet, which represent an aggregate of 16,800,000 horse-power, producing as their effect no other result than to raise the temperature of the water at the foot of the fall

$$\frac{150}{772} = \frac{1^\circ}{5} \text{ Fahr.}$$

In order to reproduce the power of 16,800,000 horses, or, in other words, to pump back the water from below to above the fall, would require an annual expenditure of not less than 266,000,000 of tons of coal, calculated at an average consumption of 4 lbs. of coal per horse-power per hour:

which amount is equivalent to the total coal consumption of the world.

In stating these facts in my inaugural address on assuming the presidency of the Iron and Steel Institute, I ventured to express the opinion that in order to utilise natural forces of this description at distant towns and centres of industry the electric conductor might be resorted to. This view was at that time unsupported by experimental data such as I have been able since then to collect, and before concluding this lecture I propose to bring some of the results of these further inquiries before your notice.

Our knowledge of electric force is, as you are aware, of very recent origin. The frictional electrical machine and the galvanic battery have been utilised for producing slight effects at great distances, thus giving rise to one of the great institutions of the present age, the Electric Telegraph. We have hitherto failed, however, to produce by means of electricity, effects in any way commensurate with those produced through the combustion and distillation of coal, which provide us with the means of driving our factories and lighting our towns with gas. It can be demonstrated, indeed, that the galvanic battery, which is dependent for its development of energy on the combustion of zinc, could never rival the effects due to the combustion of coal economically, for the simple reason that it takes 12 pounds of coal to separate a pound of zinc from its ores, while the amount of energy liberated in the combustion or oxidation of a pound of zinc is represented by 1400 heat units, whereas that by the combustion of a pound of ordinary coal is represented by 12,000 similar units.

The great discovery by Faraday of the induced current has enabled us, however, to produce electricity by the expenditure of force, and by a particular arrangement of a rotative armature and electro-magnets (which is chiefly due to my brother, Dr. Werner Siemens), the current so produced may be accumulated and directed in such a manner as to produce continuous currents, more powerful in their quantitative effects than could be accomplished by batteries or any other means.

Very powerful currents indeed are produced by means

of these machines, properly called Dynamo-Electric, by the expenditure of mechanical force only, in imparting rotative motion to an armature or keeper of cylindrical

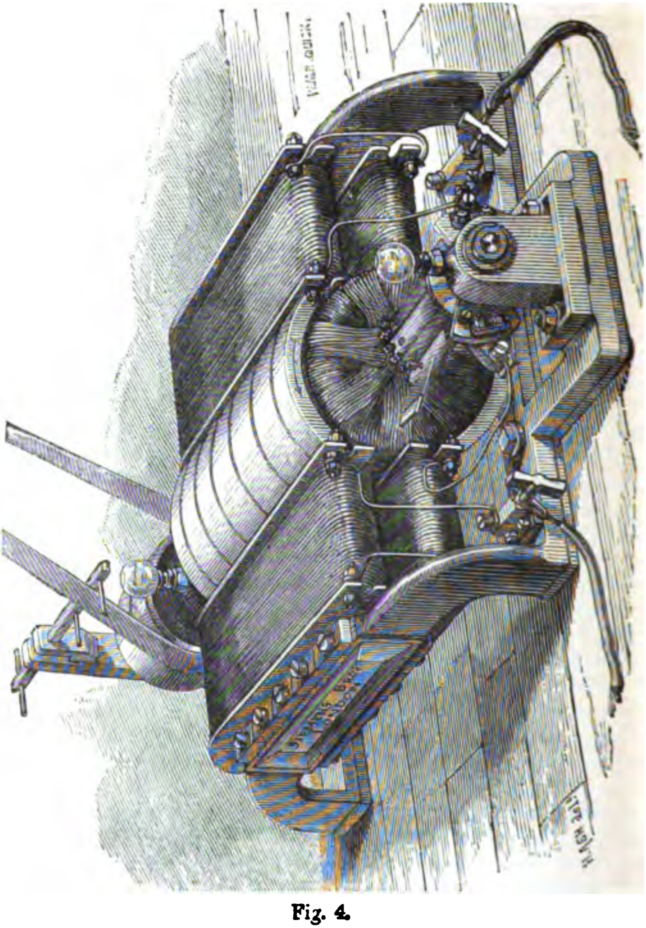

Fig. 4.

form surrounded by insulated wires, laid longitudinally upon the cylinder, and revolving with it in the magnetic field due to the polar surfaces of electro-magnets, the coils of which are excited by the very current set up through rotation in the wire upon the armature.

Thus an accumulative principle of action and reaction is inaugurated not altogether dissimilar in principle to the accumulative action already described to you in reference to the regenerative gas furnace, and as in the gas furnace temperatures can be produced limited only by the point of dissociation of combustible matter, so the intensity of electrical action producible in the dynamo-electric machine is limited only by the point of ultimate magnetisation of which iron is capable. As a matter of fact and experiment, a dynamo-electric machine such as is actually employed at the Lizard Lighthouse, weighing altogether 3 cwts. 3 qrs., is capable of converting 3·3 horse-power into electrical energy, which energy is employed for the production of an electric light equal to 4138 candle-power. The smaller machine, which I have placed before you, weighs only 2 cwts. 2 qrs., converts 2 horse-power into electrical energy, which energy may be employed for the production of an electric light equal to 1250 candles, or for producing mechanical force capable of being utilised at a distance for giving motion to machinery, for pumping water, or any other useful purpose. Experiments have shown that the amount of mechanical force that may thus be recovered is equal, or nearly equal, to one-half the force expended in the original production of the current. The diagrams placed upon the wall may serve to give you a better idea of the construction of these machines.

Let us suppose that at some central station 100 horse-power of steam or water power was employed to give motion to several dynamo-electric machines of the dimensions found most convenient in practice, and that by means of metallic conductors of suitable dimensions the electric current produced at the central station was conducted to a number of halls or factories requiring to be lighted, or to utilise mechanical power. If illumination were the only object in view, the total amount of light that could

be thus produced would be equal to 125,000 candle-power. This would be equivalent to 6250 Argand burners, each of 20 candle-power, at a consumption per burner of 6 cubic feet of gas per hour, or a total consumption of 37,500 cubic feet of gas to produce the same effect of light. This would require $3\frac{3}{4}$ tons of coal, and the electric light about as many hundredweights.

It would be fallacious to suppose, however, that in resorting to the electric light we should be satisfied with anything like the candle-power that now satisfies us in using gas, even as we are not now satisfied with the light of lamps and candles since we have become accustomed to gas-lighting. There is this further inconvenience connected with the electric light, that its rays are so intense that they must not reach our eyes without having first been softened down, either by the interposition of some semi-transparent substance, such as ground glass, or by directing the light against screens, or against the ceiling of the room, as was suggested by the Duke of Sutherland, so as to illuminate by reflection only. In making due allowance for these losses of effect there remains, however, ample margin in favour of the electric light, to make it cheaper, and certainly more brilliant than gaslight. Its practical application for large halls and places where powerful light effects are required, will therefore be a question only of time, while for domestic purposes gaslight will long continue to hold its own, owing to the greater facility which it offers of subdividing the effects of light, and of accommodating its intensity to immediate requirements by simply opening and closing an ordinary tap.

My present object, however, is not to discuss the relative merits of the two modes of illumination, but simply to show that power derived from a distant source is capable of being utilised for the production of light of a very brilliant character, a light which is comparable with solar light in showing every object in its true colour, and in producing similar chemical effects, such as the taking of photographic images.

If mechanical force is required to be distributed, the arrangements are in every respect similar to those for the

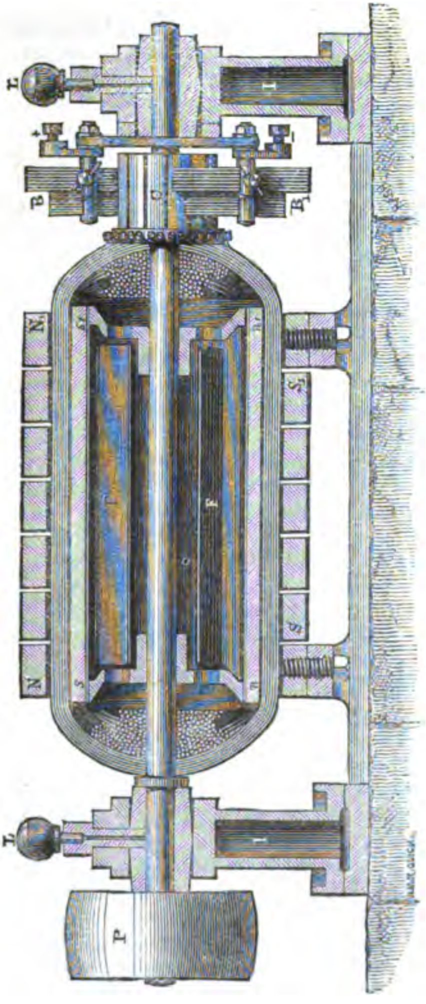

Fig. 5.

distribution of electric light, and it has been proved experimentally that the amount of power recovered at the distant station is nearly equal to half the power employed at the central station.

At first sight this loss of power may be considered large, but if we compare the cost of producing a limited amount of power by the magneto-electric machine, and by a gas or steam engine, it will be found that the magneto-electric machine recommends itself, not only by its cleanliness and by the ease with which it can be turned on and off at any moment, but that it is the cheaper machine as far as regards the consumption of coal. In working a small gas or steam engine, the consumption of fuel cannot be taken at less than 8 pounds per horse-power per hour, whereas in working a 100 horse-power steam engine on economical principles, 2, or say 2·5, pounds per hour of coal suffice to produce 1 horse-power. Suppose that 45 per cent. of the power available at the central station is reproduced at the distant one, the amount of coal per hour consumed at the distant station would be

$$2{\cdot}5 \times \frac{100}{45} = \frac{250}{45} \text{ is } 5{\cdot}6 \text{ lbs.,}$$

or 30 per cent. less than if a gas or steam engine were directly employed.

The principal objection that has been raised by electricians to the conveyance of power to distances of miles, as here proposed, is on account of the apparently rapid increase in the size of the conductor required with increase of distance. In order that the magneto-electrical machine may work under the most favourable conditions, it should have an internal resistance depending in a great measure upon the nature of the work to be performed, but not exceeding for quantitative effects one ohm or unit of resistance. If the resistance is greater, a notable proportion of the power expended will be converted into heat in the conductors, causing both loss of effect and great inconvenience. By another law, the electrical resistance of the circuit exterior to the machine should be somewhat, but not much, larger than the

internal resistance, say $1\frac{1}{2}$ unit; the external resistance is composed of two elements, namely, the conductor and the resistance of the electric lamp, or electro-magnetic engine, which latter may be taken as amounting also to one unit, leaving only half a unit available for the conductor. These conditions determine really the size of the conductor for any distance to which the current has to be conveyed.

Suppose the distance to be half a mile, a copper wire of 0·23 inch diameter will produce the half unit resistance to be desired, which is already a wire of considerable dimensions for the purpose of working a single lamp. If the distance be doubled, wire of the same thickness would give twice the electrical resistance, and in order to reduce it again to half a unit, its sectional area must be doubled; we have thus a conductor of double length and sectional area, and therefore of four times the weight, and relying upon this calculation it is argued that the weight of the conductor must increase as the square of the distance: so that a conductor of 30 miles' length would require to be $(60)^2 = 3600$ times the weight of the half-mile conductor, and this enormous increase in weight would certainly be required if the object to be accomplished was the working of one electric lamp by a dynamo-electric machine.

My critics have, however, fallen into the error of overlooking the fact that half a unit resistance is the same for a circuit capable of working one lamp as it is for working 100 or 1000 lamps. Electricity is not conducted upon the conditions appertaining to a pipe conveying a ponderable fluid, the resistance of which increases with the square of the velocity of flow: it is, on the contrary, a matter of indifference what amount of energy is transmitted through an electric conductor, the only limit is imposed by the fact that in transmitting electrical energy the conductor itself retains a certain amount proportional to that transmitted, which makes its appearance therein in the form of heat. If this heat was allowed to accumulate, the electrical resistance of the conductor would increase in proportion to such increase, and a point might be reached where fusion of the wire would ensue.

I will now connect the spiral of platinum wire I hold in

my hand with the dynamo-electrical machine which is working a hundred yards off, and you will discover in a moment that the wire is red-hot, owing to the amount of electricity that has been passed through a wire of so small a sectional area.

The real power of transmission of an electric current depends, therefore, upon its capability to discharge its heat to surrounding objects, and it will be readily conceived that a wire of sixty times the sectional area and sixty times the length of another wire is capable of radiating away $60\sqrt{60} = 460$ times as much heat per hour as the smaller conductor, and that 460 machines or lights may be supplied through it without causing inconvenience.

When, some weeks ago, I had occasion to use this argument before the Institution of Civil Engineers, your President, who happened to be at the meeting, immediately recognised its force, and, with the fertility of mind for which he is so remarkable, there and then suggested a means by which the transmitting power of a large electrical conductor might be almost indefinitely increased by giving it the form of a hollow tube through which water might be made to flow. It is evident that cold water flowing through such a conductor would prevent an inconvenient accumulation of heat in the metal, and it would not be difficult to introduce and discharge the flowing water at intervals from the pipe without interfering with the necessary insulation of the conductor from the earth.

Our last experiment proved that intense heat can be generated in the electric conductor, and I now propose to bring before you another simple experiment, to show how readily the heat so generated may be employed for heating water. I will immerse the spiral coil of platinum wire which I hold in my hand in a glass jar containing about two pints of water, and after closing the electric circuit you will perceive, in the course of a minute or two, that the water is brought to the boiling point, nor would this mode of heating water in small quantities be expensive if currents were laid on to our houses from dynamo-electric machines, and who knows whether, in the electrical age towards which we seem to be gravitating, the apparatus

before you may not be the common coffee machine of the day.

After this digression, let us return for a moment to my proposal of last year to convey 1000 horse-power a distance of 30 miles through a conductor 3 inches diameter.

The electrical resistance of this conductor would be ·18 of a unit, and supposing that the total resistance in circuit was made 2½ units, which, as I before stated, gives a favourable working condition, it follows that

$$\frac{\cdot 18}{2\cdot 5} \times 1000 = 72 \text{ horse-power}$$

would be expended in heating the conductor.

This would represent about 15 lbs. of coal per hour, a quantity quite insufficient to raise a mass of 1900 tons of copper, with a surface of 132,000 square feet, to a sensibly heated condition. So far from admitting therefore that I have overstated my case regarding the capability of my large electrical conductor, I am convinced, on the contrary, that its sectional area might be safely reduced to one-half that previously given (or its diameter to 2 inches), whereby its cost would also be reduced one-half.

It would not be necessary to seek on the other side of the Atlantic for an application of this mode of transmitting the natural force of falling water, as there is perhaps no country where this force abounds to a greater extent than on the west coast of Scotland, with its elevated lands and heavy rainfalls. You have already conducted the water of one of your high-level lochs to Glasgow, by means of a gigantic tube, and how much easier would it be to pass the water in its descent from elevated lands through turbines, and to transmit the vast amount of force that might thus be collected, by means of stout metallic conductors, to towns and villages for the supply of light and mechanical power!

Practical difficulties would, no doubt, have to be contended with, regarding chiefly the proper distribution of the main current over its numerous branches. This subject has latterly occupied my attention in some degree, and admits, I believe, of a satisfactory solution.

It is not my desire, however, to occupy your attention with matters of practical detail of this kind, nor to enlarge further upon the advantageous applications that could be made of the electricity produced by natural forces for other purposes, such as the separation of copper and other metals from their combinations.

Much might be said, also, regarding the utilisation of the irregular force of the wind, which represents an enormous aggregate of available energy capable of collection and distribution in countries where other sources of energy may be wanting.

A number of windmills, such as may be constantly seen working in Holland for the drainage of the land might, for instance, be employed to raise water, by pumping, to an elevated lake or reservoir, whence the power could be drawn off by means of hydraulic motors when required, and might be conducted electrically to centres of habitation.

Other modes of utilising solar energy, either in the form of the direct ray or in other modified forms, might be added to the illustrations I have selected. In dwelling probably too much upon these, I fear to have taxed your patience, and to have laid myself open to the reproach of having betrayed a preference for those branches of the general subject with which I have been professionally or otherwise connected. I do not deny such a charge, but plead for my excuse that those are the very branches upon which I may possess some right to speak, with some chance of engaging your interest.

Whether or not I have been in the least degree successful in accomplishing this is a question which you will judge, I hope, rather by my desire to discharge the duty I had undertaken than by the standard furnished you by my predecessors in this place.